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Saturated Hydraulic Conductivity of Semiarid Soils: Combined Effects of Salinity, Sodicity, and Rate of Wetting

G. J. Levy, D. Goldstein, and A. I. Mamedov*

ABSTRACT

Combined effects of soil conditions (wetting rate), soil sodicity, and salinity on soil saturated hydraulic conductivity (HC) have not been studied systematically and were the objective of our study. We examined the effects of (i) exchangeable sodium percentage (ESP, 1–20) and fast wetting (50 mm h^{-1}) and leaching with distilled water on the HC of 60 Israeli soils (7–70% clay); and (ii) wetting rate (2 or 50 mm h^{-1}), ESP and water salinity (distilled water or saline water, 2 dS m^{-1}) on the HC of 16 selected samples. Results of the first experiment showed that (i) steady state HC of medium- and fine-textured soils was lower than 2 cm h^{-1} already for nonsodic soils, and (ii) the adverse impact of sodicity on the HC strongly depended on soil texture. The second experiment revealed that in the loamy sand rate of wetting had no effect on the HC beyond that of sodicity and salinity. In the loam, sandy clay and clay soils a significant triple interaction among water quality, wetting rate and ESP in their effect on HC existed. In the absence of electrolytes, the impact of fast wetting (slaking) and swelling on the HC was most notable, mainly at the intermediate sodicity levels (ESP = 5–10). Use of saline water significantly reduced the impact of fast wetting and swelling on the HC. Our results suggested that combined effects of salinity, wetting rate, and sodicity on the HC were complex and should thus be considered simultaneously when estimating soil HC.

Soil hydraulic conductivity depends on the composition of the exchangeable cations and the composition and concentration of the electrolytes in the soil solution (Quirk and Schofield, 1955), as well as on soil texture (Shainberg et al., 2001). The HC decreases with an increase in the ESP (McIntyre, 1979) and the decrease in the total electrolyte concentration of the soil solution. The reduction in the HC has been attributed mainly to swelling and dispersion of the soil clays (Quirk and Schofield, 1955).

The adverse effects of soil sodicity and scarcity of electrolytes on soil hydraulic properties have been studied extensively (see recent reviews by Rengasamy, 1998; Sumner and Naidu, 1998; Levy, 2000, and references cited therein). These studies have demonstrated the significant role of soil inherent properties (e.g., soil texture, clay mineralogy, pH, and sesquioxide and lime content) in determining the response of soils to sodic conditions. The HC of soils with high proportion of 2:1 clay minerals, high pH, and low sesquioxides content was found to be susceptible to sodic conditions, with the magnitude of the decrease in HC being strongly dependent on the electrolyte concentration in the soil solution (Shainberg and Letey, 1984).

Unlike inherent soil properties, the effects of temporal changes in the conditions prevailing in the soil (e.g., rate of wetting, antecedent moisture content and aging duration) on the response of soils to sodic conditions have received less attention (Shaw et al., 1998). As a result, the experimental setup under which many of the investigations of the response of the HC to sodicity has been studied represented extreme conditions which do not necessarily occur in the field. For instance, disturbed soil samples were subjected to fast wetting and thereafter to an immediate measurement of soil HC. Fast wetting of aggregates results in their slaking (Panabokke and Quirk, 1957) and in a subsequent shift in the pore size distribution toward smaller pores (Kay and Angers, 2000). Aggregate slaking and the subsequent change in pore size distribution may reduce the HC, infiltration rate, and lead to runoff and erosion (Lebron et al., 2002; Levy and Mamedov, 2002).

The lack of an aging period between the wetting and the measurement of the HC prevented the opportunity for aggregates to regain their stability via formation of new intra- and interparticle cohesive bonds (Shainberg et al., 1996). Hence, under these conditions the soils were noted to be very susceptible to the effects of sodicity, salinity, and soil inherent properties (McIntyre, 1979; Shainberg and Letey, 1984; Levy et al., 1998). However, in a natural environment, the soils are often exposed to slow wetting that prevents aggregate slaking and could also at times stay moist for a while before being exposed to rain or an irrigation event. Thus, there is a need to evaluate susceptibility of soil HC to sodicity under conditions that better reflect the situation of the soil in the field.

A number of studies have recently demonstrated the importance of rate of wetting and duration of aging on the saturated HC of soils. Moutier et al. (1998) evaluated the effects of aging on the HC of a clay soil at two levels of sodicity, 0 and 10%. Different aging durations were applied through different leaching times. It was noted for both sodicity levels that prolonged leaching (20 h) of the soil maintained significantly higher HC compared with leaching for a short period of 3 h (Moutier et al., 1998). In an additional study, Moutier et al. (2000) studied the effects of rate of wetting on the HC of two calcium saturated clay soils. The results indicated that

G.J. Levy and D. Goldstein, Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet-Dagan 50-250, Israel; A.I. Mamedov, USDA-ARS-MWA, National Soil Erosion Research Laboratory, West Lafayette, IN 47907. Contributions from the Agricultural Research Organization, The Volcani Center, Bet-Dagan, Israel. No. 609/2004 series. Received 7 July 2004. Soil & Water Management & Conservation. *Corresponding author (amrakh@purdue.edu).

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Abbreviations: ESP, exchangeable sodium percentage; HC, hydraulic conductivity; HCo, initial hydraulic conductivity; HCss, hydraulic conductivity at steady state; RHC, relative hydraulic conductivity at steady state.

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when the soil samples were leached with a solution containing electrolytes, the HC depended on the rate of wetting; that is, the slower the wetting, the higher the HC. However, on leaching with distilled water, a decrease in HC was noted, irrespective of the wetting rate. It was concluded that clay swelling became the governing process, and thus led to the reduction in the HC (Moutier et al., 2000). Shainberg et al. (2001) studied the HC of a number of soils with ESP $\leq$ 10 leached with distilled water as a function of wetting rate. The results indicated that the HC values at the beginning of the leaching were higher for slow wetting compared with fast wetting. Furthermore, Shainberg et al. (2001) observed that the HC of sodic soils decreased more steeply and to lower values with the increase in the rate at which the soil was wetted.

In continuation of the aforementioned studies, the objective of this study was to determine, systematically, the dependence of the effects of rate of wetting on soil HC on (i) soil sodicity and (ii) the electrolyte concentration of the percolating solution, in semiarid soils of varying in texture.

MATERIALS AND METHODS

Soils

Soil samples from cultivated fields, representing four main soil types in Israel were chosen for this study: a loamy sand (Typic Haploxeralf), a loam (Calcic Haploxeralf), a dark brown sandy clay (Chromic Haploxerert), and a dark brown clay soil (Typic Haploxerert). The soils were predominantly smectite with kaolinite, illite, and calcite present in small amounts (Banin and Amiel, 1970). Sixty samples with naturally occurring ESP levels in the cultivated layer (0–250 mm) from the four soil types were brought to the laboratory. The ESP levels studied were <2% (very low), ≈5% (low), ≈10% (medium), and ≈20% (high). Divergence in sodicity level within a soil type was due to differences in water quality used for irrigation (fresh water, treated effluent, and saline-sodic water) or to soil leveling that was done in the 1960s. Selected physical and chemical properties of the soils (Table 1) were determined by standard analytical methods (Page et al., 1986; Klute, 1986).

Hydraulic Conductivity Studies

Two sets of experiments were performed. In the first set, the HC of the 60 samples was studied. Soil columns were prepared by packing 120 g of air-dried samples (0–2 mm) in four portions of 30 g each into small cylinders (5.4 cm in diam. with a metal screen covered with 1.0 cm sand at the bottom). After adding a soil portion, the soil was distributed evenly and slightly tapped to obtain field soil bulk density. A filter paper was placed at the surface of the soil to minimize soil disturbance. After packing, the soil columns were wetted from below with distilled water at rate of 50 mm h^{-1} (fast) using a peristaltic pump. Following the wetting, the bulk density of the samples decreased due to clay swelling; the magnitude of the decrease in bulk density increased linearly with the increase of clay content (Fig. 1). When the water level reached the top of the sample, the flow direction was reversed and the columns were leached from the top with a constant head device. For each individual treatment (i.e., soil type, ESP, water quality, and wetting rate), the head was adjusted to provide an initial flux of ≈350 mL h^{-1}. During leaching, the leachate was collected continuously in 30-mL tubes that were placed in a fraction collector; its volume, pH, and electrical conductivity were measured; and the HC was calculated. Leaching was continued until no change in leachate volume was noticed in five consecutive tubes. Each treatment was replicated two to four times to obtain a coefficient of variation of <10% in the calculated HC data among repetitions. Results were analyzed statistically.

In the second set of experiments, we used four samples varying in ESP from each soil type (the first four samples for each soil type appearing in Table 1, totaling 16 samples). After packing the samples in columns as described above, the soil columns were wetted from below at 50 mm h^{-1} (fast rate) or 2 mm h^{-1} (slow rate) using a peristaltic pump. Two levels of salinity were used: (i) distilled water (electrical conductivity of 0.004 dS m^{-1}) to simulate rain, and (ii) saline water (electrical conductivity of 2.0 dS m^{-1}) to simulate the salinity level in Israeli treated waste water commonly used for irrigation of orchards and field crops. Sodium chloride (NaCl) and calcium chloride dehydrate ($CaCl_2 \cdot 2H_2O$) were used to prepare the saline solutions of 20 $mmol_c$ L^{-1} concentration. The sodium adsorption ratio of each particular saline solution was adjusted to the level of the ESP of the soil sample tested based on the nomogram for sodium adsorption ratio–ESP relationship published by the U.S. Salinity Laboratory (Richards, 1954). After completion of the wetting, flow direction was reversed and the experiments continued as described above for the former set of experiments.

RESULTS AND DISCUSSION

Two parameters were used to evaluate the effects of the treatments on soil HC, the initial hydraulic conductivity (HCo) (i.e., the HC measured at the beginning of the leaching from the top, ≈0.3–0.5 pore volume), and the apparent steady state hydraulic conductivity (HCss) (i.e., the HC that was approaching asymptotically a steady state value) or the relative hydraulic conductivity (RHC) calculated as the ratio of the measured HCss to the HCo.

The marked dependence of the HCo and HCss on clay content, for the 60 samples subjected to fast wetting and leached with distilled water, is presented in Fig. 2. Since no dispersed clay was noted in the leachates, the HC parameters were expected to be affected by aggregate slaking following the fast wetting and clay swelling. Both the HC parameters showed an exponential type of decay with the increase in clay content. More specifically, only samples with clay $\leq$ 14% exhibited high HCo and HCss values of >4 and >2 cm h^{-1}, respectively (Fig. 2). This observation indicated that the HC of medium- and fine-textured soils from semiarid region subjected to fast wetting is low already for samples having ESP ≈ 2.

A detailed analysis of the effects of ESP on the HCo after fast wetting has shown, similar to former studies (Horn, 1983; Abrol et al., 1988; Lebron et al., 2002), that the HCo for each soil type decreased exponentially with the increase in sodicity (Fig. 3). However, the rate of decay in HCo with the increase in sodicity depended on soil texture; the exponent (absolute value) of the equation increased significantly with the increase in clay content from 0.061 to 0.48 (Fig. 3). A similar observation was noted for the RHC (data not presented). Our find-

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ings suggested that the HC (both HCo and HCss) of semiarid smectitic clay soils was very susceptible to conditions of fast wetting with distilled water and ESP > 5.

Effects of Wetting Rate and Salinity

Initial Hydraulic Conductivity

The electrical conductivity of the leachate in the case of leaching with saline water was dictated by the electrical conductivity of the leaching solution (2.0 dS m^{-1}). In the case of leaching with distilled water, the electrical conductivity in the first fraction collected (15–20 mL), which corresponds to ≈1/3 pore volume, in all cases was >0.4 dS m^{-1}. Soil clays were not expected to disperse at the electrical conductivity level found in the leachtes of either type of leaching solution. Thus, HCo was expected to be affected mainly by aggregate slaking and by clay swelling (Oster et al., 1980; Shainberg et al.,

Table 1. Some physical and chemical properties of the soils studied. In the first set of the experiments all soil samples were used. In the second set of the experiments only the first four samples of each soil type were used.

Soil	Classification	Particle-size distribution: Sand	Silt	Clay	CEC†	ESP‡	$CaCO_3$	OM§
		g kg^{-1}			$cmol_c$ kg^{-1}	%	g kg^{-1}	g kg^{-1}
Loamy sand	Typic Rhodoxeralf	850	60	90	9.41	1.10	13.2	4.2
		855	50	95	9.16	4.60	14.5	3.4
		875	45	80	7.76	10.20	25.4	4.0
		860	45	95	7.51	20.30	20.1	3.0
		870	60	70	7.87	0.97	8.7	3.4
		865	60	75	8.34	1.82	12.3	4.2
		870	50	80	7.46	1.94	9.4	5.4
		810	50	140	9.58	1.08	10.2	7.6
		870	50	80	8.75	1.10	12.6	6.0
		870	50	80	7.29	14.67	7.9	3.2
Loam	Calcic Haploxeralf	413	362	225	17.68	2.10	182.4	12.2
		453	335	212	17.51	5.50	184.4	12.0
		480	280	240	20.07	8.99	174.3	11.2
		550	150	300	20.62	20.25	161.4	9.7
		725	100	175	13.37	0.98	135.8	9.4
		750	90	160	12.74	1.67	127.2	8.4
		625	125	250	16.45	4.40	91.3	8.5
		675	125	200	17.88	6.77	102.3	9.6
		600	166	234	14.86	2.71	168.7	11.6
		580	180	240	20.76	19.65	154.0	6.8
		550	194	256	16.38	5.70	174.5	12.6
		650	100	250	13.79	2.68	131.7	14.3
		595	180	225	19.77	9.51	133.8	11.3
		612	190	198	16.30	10.89	164.8	11.2
Sandy clay	Chromic Haploxerert	465	154	381	34.76	1.63	96.2	11.0
		458	156	386	33.40	5.50	85.0	16.7
		420	170	410	45.94	9.22	128.8	12.7
		340	180	480	31.54	21.22	205.2	4.5
		475	113	413	40.72	1.45	87.3	15.2
		475	115	410	37.23	5.39	88.4	16.9
		475	110	415	32.22	7.29	103.7	15.4
		340	220	440	32.40	16.90	216.1	2.6
		450	130	420	38.04	4.45	79.0	12.4
		390	210	400	33.20	10.10	156.0	8.1
		325	280	395	29.72	4.04	182.9	10.8
		425	170	405	31.43	3.69	134.4	14.3
		380	240	380	32.78	1.15	193.1	7.1
		305	245	450	41.97	2.15	193.5	7.7
Clay	Typic Haploxerert	125	235	640	66.20	2.40	73.0	27.2
		150	304	546	56.65	4.70	156.0	15.9
		145	225	630	59.79	9.25	88.4	10.0
		213	188	600	49.37	20.40	127.4	6.3
		263	238	500	43.15	4.37	218.3	9.6
		280	235	485	46.59	10.47	186.5	7.8
		280	240	480	42.54	7.16	151.2	11.2
		250	210	540	46.47	15.12	130.1	8.2
		145	343	513	57.43	1.64	202.0	17.6
		200	275	525	53.05	3.20	156.0	16.2
		250	230	520	40.60	20.16	125.8	6.7
		138	238	625	60.26	6.60	167.6	17.8
		163	187	650	60.24	1.18	102.7	28.6
		250	138	612	59.97	0.87	49.2	16.8
		138	213	650	75.90	1.08	40.2	19.2
		150	210	640	65.81	1.32	45.6	23.4
		125	238	638	51.88	8.13	204.7	19.6
		153	160	688	59.19	2.71	83.8	33.4
		150	175	675	54.83	4.65	64.2	17.0
		150	163	688	64.17	2.51	66.8	44.0
		150	163	688	64.78	3.68	72.2	52.7
		150	160	690	56.90	11.56	59.1	41.4

† CEC = cation exchange capacity.
‡ ESP = exchangeable sodium percentage.
§ OM = organic matter.

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2001). The HCo data for each soil type were subjected to a multifactor ANOVA (SAS Institute, 1995). In cases where significant interactions were noted among main treatments (water quality, wetting rate, and ESP), significance of differences among HCo of individual treatments was determined using a single confidence interval value (e.g., Fig. 4).

In the loamy sand, wetting rate had no significant effect on the HCo (Table 2). This finding was in agreement with former studies that had reported the rate of soil wetting did not affect water flow in the loamy sand (Mamedov et al., 2001; Shainberg et al., 2001). Clay and silt contents in the loamy sand were low (Table 1), and therefore this soil was poorly aggregated. Consequently, the sandy matrix of this soil, rather than aggregate slaking by fast wetting, determined its HCo, which was by far higher than the HCo of the other soils tested (Fig. 4). A significant interaction was noted between water quality and ESP (Table 2). As expected, based on clay swelling considerations (e.g., McNeal and Coleman, 1966; Oster et al., 1980), HCo was higher when saline water was used compared with distilled water, and decreased for both water qualities with an increase in soil sodicity.

For the loam, sandy clay, and clay, a significant interaction between water quality, wetting rate, and ESP existed with regard to the effects of these three variables on HCo (Table 2). Following the significant differences in the texture among these three soils (Table 1), only two phenomena were shared by the three soils: (i) the HCo when distilled water was used was generally lower than that obtained when saline water was used; and (ii) for distilled water, HCo decreased with the increase in soil ESP. These observations reemphasized the significant role of water quality and soil sodicity in determining the HC of the soil at different conditions prevailing in the soil. Other observations were unique to each soil.

The HCo in the loam was not affected by rate of wetting when distilled water was used. An aggregate stability test, performed on samples from the same fields from which samples were taken for the current study, indicated that the loam was characterized by aggregates with low stability (Levy et al., 2003). Evidently, aggregate disintegration took place even when wetting at a slow rate was used. Consequently, for any given sodicity level, comparable HCo levels were obtained for fast and slow wetting (Fig. 4). When saline water was used, the effect of wetting rate was pronounced only at ESP = 10 and 20. Use of saline water decreased swelling and deterioration in aggregate stability; therefore at slow wetting the aggregates were less sensitive to disintegration during wetting and the HCo was higher compared with fast wetting. Conversely, at the lower ESP levels (2 and 5), rate of wetting had no effect on HCo when saline water was used (Fig. 4). The impact of sodicity at these levels on aggregate stability was negligible; the use of saline water combined with slow wetting could not enhance the stability of the aggregates beyond their inherent level, and HCo was therefore similar to that obtained when fast wetting was studied. Moreover, the clay content of the samples with ESP = 2 or 5 was lower than that in the samples with the high ESP (Table 1). This fact probably also contributed to the inability to distinguish between fast and slow wetting in the low ESP samples.

The HCo in the sandy clay and the clay was, in general, favorably affected by slow wetting in comparison to fast wetting for samples of similar salinity and sodicity combination (Fig. 4). This observation was attributed to the high clay content in these two soils (Table 1); the higher the clay content, the greater the importance of aggregate slaking (or its prevention) in controlling water movement in the soil (Mamedov et al., 2001; Shainberg

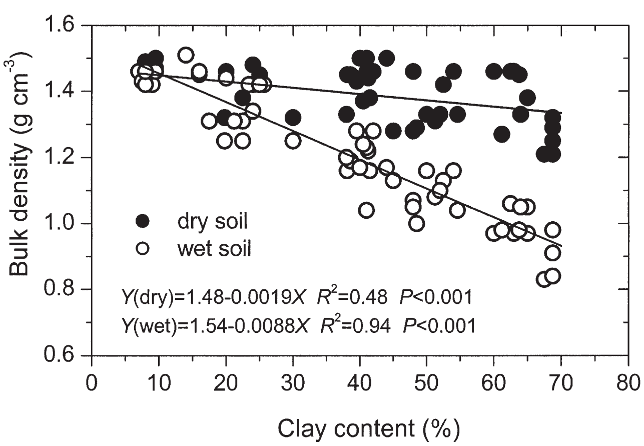

Fig. 1. Bulk density of the dry and wet soil samples in the columns as a function of clay content.

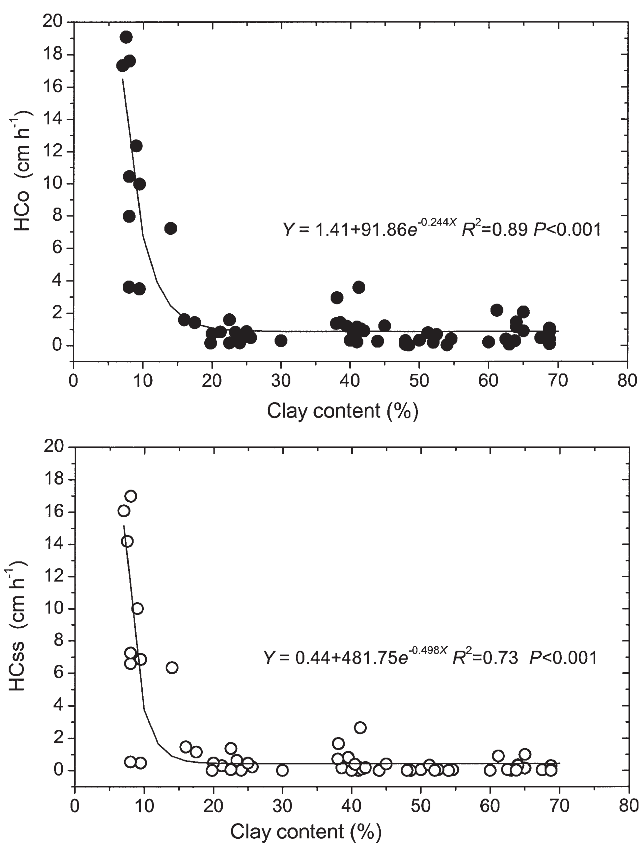

Fig. 2. Initial (HCo) and steady state (HCss) hydraulic conductivity as a function of clay content for the 60 samples subjected to fast wetting and leaching with distilled water.

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et al., 2001). In addition, the high clay content of the two soils made them sensitive to clay swelling under conditions of increased sodicity and absence of electrolytes in the soil solution. Consequently, leaching with saline water resulted, in most cases, in higher HCo values compared with leaching with distilled water. Regarding sodicity, with the exception of the sample with ESP = 5 in the sandy clay, HCo in this soil decreased with the increase in sodicity. In the clay soil, HCo values for samples with ESP ≥ 5 were comparable and significantly lower than those for ESP = 2 (Fig. 4). It is postulated that already at the low ESP level of 5, clay swelling in a soil containing ≈60% clay is extremely severe and reduced the HCo to <1 mm h^{-1}; further increasing the ESP has only a limited effect on the HCo.

Relative Hydraulic Conductivity at Steady State

Following leaching with 10 to 15 pore volumes, depending on soil type, HCss was attained. In many cases, HCss was lower than the HCo. However, to be able to compare the effects of the treatments on the HCss, we preferred to express the latter in terms of RHC. With the exception of the loamy sand, a multifactor ANOVA (SAS Institute, 1995) showed that a significant interaction between water quality, wetting rate, and ESP existed with regard to the effects of these three variables on the RHC in each individual soil (Table 3). In the loamy sand, significant interactions were noted between water quality and (i) wetting rate and (ii) ESP. The existence of the aforementioned interactions suggested that the combined effects of these variables on the RHC were complex (See Fig. 5–8).

The RHC in the loamy sand was affected by the rate of wetting when distilled water was used (Fig. 5). Analysis of variance for the RHC data obtained with distilled water showed a significant interaction between rate of wetting and ESP. Thus, a single confidence interval was added to Fig. 5. For fast wetting, the RHC decreased linearly with the increase in sodicity (Fig. 5a). The electrical conductivity of the effluent was <0.05 dS m^{-1}, which is below the flocculation value of smectites with ESP = 5 (Oster et al., 1980). However, no dispersed clay was observed in the leachate. Because the loamy sand was poorly aggregated, aggregate slaking was not expected to affect the RHC. Swelling of the clay in a loamy sand cannot solely explain the reduction of >80% in the HCo (RHC < 20%) for the sample with ESP = 20 (Pupisky and Shainberg, 1979). It is postulated, therefore, that the gradual decrease in RHC with the increase in ESP may arise from possible greater destabilization

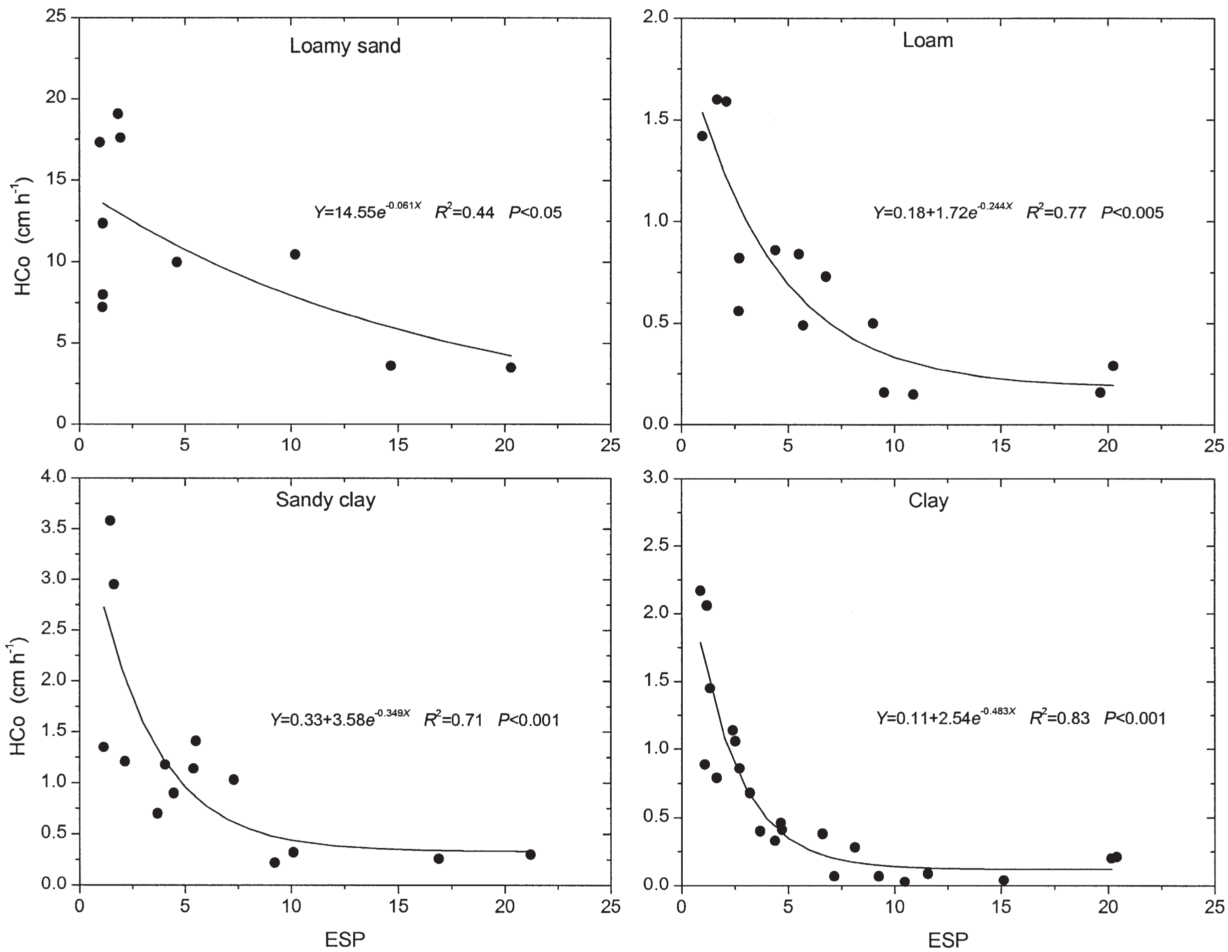

Fig. 3. Initial hydraulic conductivity (HCo) as a function of exchangeable sodium percentage (ESP) for the 60 samples subjected to fast wetting and leaching with distilled water. Data are presented for each soil type separately.

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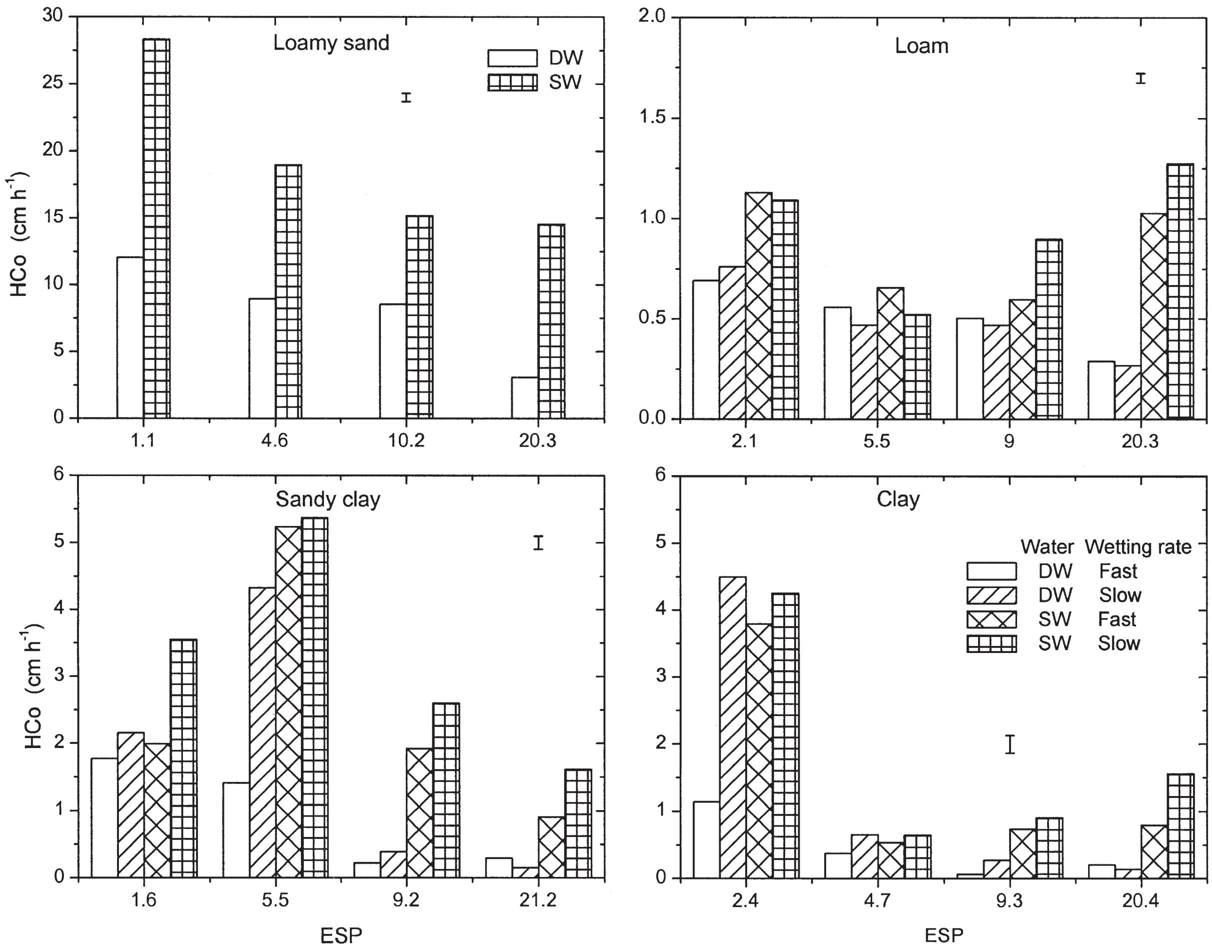

Fig. 4. Initial hydraulic conductivity (HCo) as a function of exchangeable sodium percentage (ESP), water quality, and rate of wetting for the selected soil samples studied. Bars indicate a single confidence interval value at $P = 0.05$. DW = distilled water, SW = saline water.

of the clay that was coating the sand particles (Pupisky and Shainberg, 1979) with the increase in ESP. It is further suggested that local movement and deposition of the detached clay particles in smaller pores, combined with greater swelling (due to the higher ESP), could result in the narrowing of the water-conducting pores and the low RHC. When slow wetting was employed, a convex-type curve (a logarithmic-type relationship) described the association between RHC and ESP, indicating that a substantial decrease in RHC was to take place only beyond a threshold ESP level (Fig. 5a). At up to ESP = 10, the RHC remained high (>90%), and only at ESP = 20 did the RHC decrease to <50%. Slow wetting minimized the destabilization of the clay skin that coated the sand particles. Therefore, swelling and possibly some clay dispersion remained the main mechanism to adversely affect the HC. Thus, in the current study, only when the ESP = 20 was the degree of swelling and dispersion high enough to force a significantly lower RHC compared with those obtained at lower ESP levels.

Leaching the loamy sand with saline water resulted in high RHC values (>90%) that were independent of rate of wetting and of soil sodicity (Fig. 5b). Use of saline water limited clay swelling to a degree where its effects on the HC became negligible. In addition, it prevented the previously discussed adverse effect of fast wetting on the destabilization of the soil clay.

The response of the loam to leaching with distilled water depended on both the rate of wetting and level of sodicity. Fast wetting resulted in an exponential type decay in the RHC with the increase in ESP (Fig. 6), while for slow wetting RHC decreased linearly with the increase in sodicity (Fig. 6a). When an exponential equation was used to describe the relationship for both wetting rates, the absolute value of the exponent at slow wetting was significantly lower than in fast wetting rate (Table 4). The texture of the loam enabled aggregate formation; however, because of the high silt/clay ratio and the medium clay content in this soil (Table 1), it was characterized by relatively weak aggregates (Ben-Hur et al., 1985; Shainberg et al., 1992) and low HCo values (Fig. 4). In the loam, even slow wetting had been noted to slake aggregates (Shainberg et al., 2001; Mamedov et al., 2001). The RHC values for the lowest and highest ESP levels were similar for the fast and slow wetting. In the two intermediate ESP levels (5 and 10), the RHC were lower for the fast wetting than for the slow wetting. It is suggested that at these intermediate ESP levels, (i) fast wetting weakened and slaked the aggregates to such an extent that, during leaching, some detachment of soil particles had occurred by the

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Table 2. Multifactor ANOVA for effects of water quality (WQ), wetting rate (WR), and exchangeable sodium percentage (ESP) in each soil type on the initial hydraulic conductivity.

Soil type	Source of variation	df	Sum of squares	*F* ratio	Significance
Loamy sand	WQ	1	1193	440.7	***
	WR	1	4.433	1.637	
	WQ × WR	1	10.05	3.711	
	ESP	3	356.1	43.84	***
	WQ × ESP	3	218.5	26.91	***
	WR × ESP	3	12.79	1.575	
	WQ × WR × ESP	3	9.633	1.186	
	error	16	80.22		
	corrected total	31	1847		
Loam	WQ	1	1.318	733.7	***
	WR	1	0.008	4.738	*
	WQ × WR	1	0.026	14.65	*
	ESP	3	0.619	114.8	***
	WQ × ESP	3	0.736	136.6	***
	WR × ESP	3	0.079	14.59	***
	WQ × WR × ESP	3	0.070	12.95	***
	error	16	0.029		
	corrected total	31	2.887		
Sandy clay	WQ	1	21.20	540.8	***
	WR	1	6.056	154.5	***
	WQ × WR	1	0.012	0.305	
	ESP	3	51.67	439.4	***
	WQ × ESP	3	4.197	35.69	***
	WR × ESP	3	1.865	15.86	***
	WQ × WR × ESP	3	4.986	42.40	***
	error	16	0.627		
	corrected total	31	90.62		
Clay	WQ	1	2.556	108.4	***
	WR	1	3.111	131.9	***
	WQ × WR	1	0.499	21.18	***
	ESP	3	43.93	621.1	***
	WQ × ESP	3	4.513	63.81	***
	WR × ESP	3	5.932	83.88	***
	WQ × WR × ESP	3	5.274	74.57	***
	error	16	0.377		
	corrected total	31	66.19		

* Significant at the 0.05 level.
*** Significant at the 0.001 level.

shear stress of the flowing water; and (ii) an immediate deposition of the detached particles at narrow pores, coupled with clay swelling, contributed to the lower RHC levels compared with those obtained in the slow wetting, where detachment of particles by the flowing water was probably negligible. At ESP = 20, severe clay swelling, whose effect on pore size distribution was enhanced by the high silt/clay ratio in the loam, determined the RHC of the soil, overriding the effects of rate of wetting (Fig. 6a). Conversely, at ESP = 2, clay swelling was negligible and could not significantly reduce the size of the water conducting pores; thus, the RHC values for fast and slow wetting were similar as was noted for the corresponding HCo values (Fig. 4).

Table 3. Analysis of variance for effects of water quality (WQ), wetting rate (WR), and exchangeable sodium percentage (ESP) in each soil type on the relative hydraulic conductivity at the end of the leaching.

Soil type	Source of variation	df	Sum of squares	*F* ratio	Significance
Loamy sand	WQ	1	4459	133.7	**
	WR	1	2007	60.17	**
	WQ × WR	1	649.1	19.46	**
	ESP	3	6700	66.95	**
	WQ × ESP	3	6552	65.47	**
	WR × ESP	3	365.9	3.655	
	WQ × WR × ESP	3	185.3	1.852	
	error	16	533.8		
	corrected total	31	21453		
Loam	WQ	1	29022	1227	***
	WR	1	858.9	114.8	***
	WQ × WR	1	270.8	0.121	***
	ESP	3	9232	280.9	***
	WQ × ESP	3	3336	126.0	***
	WR × ESP	3	1149	14.80	***
	WQ × WR × ESP	3	141.9	12.02	*
	error	16	260.9		
	corrected total	31	44355		
Sandy clay	WQ	1	20681	1119	***
	WR	1	3567	193.2	***
	WQ × WR	1	999.3	54.11	***
	ESP	3	10466	188.9	***
	WQ × ESP	3	2175	39.26	***
	WR × ESP	3	1589	28.68	***
	WQ × WR × ESP	3	1751	31.61	***
	error	16	295.5		
	corrected total	31	41526		
Clay	WQ	1	14044	1158	***
	WR	1	4123	340.0	***
	WQ × WR	1	85.80	7.075	*
	ESP	3	8409	231.1	***
	WQ × ESP	3	3692	101.5	***
	WR × ESP	3	2789	76.69	***
	WQ × WR × ESP	3	2375	65.31	***
	error	16	194.0		
	corrected total	31	35714		

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

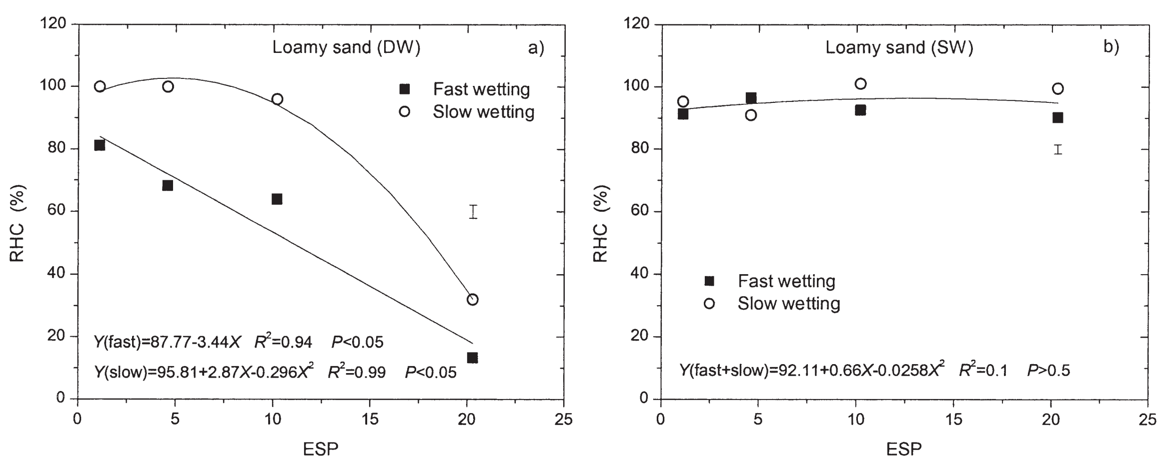

Fig. 5. Relative hydraulic conductivity at steady state (RHC) in the loamy sand as a function of exchangeable sodium percentage (ESP), water quality, and rate of wetting: (a) distilled water (DW) treatment; (b) saline water (SW) treatment. Bars indicate a single confidence interval value at $P = 0.05$.

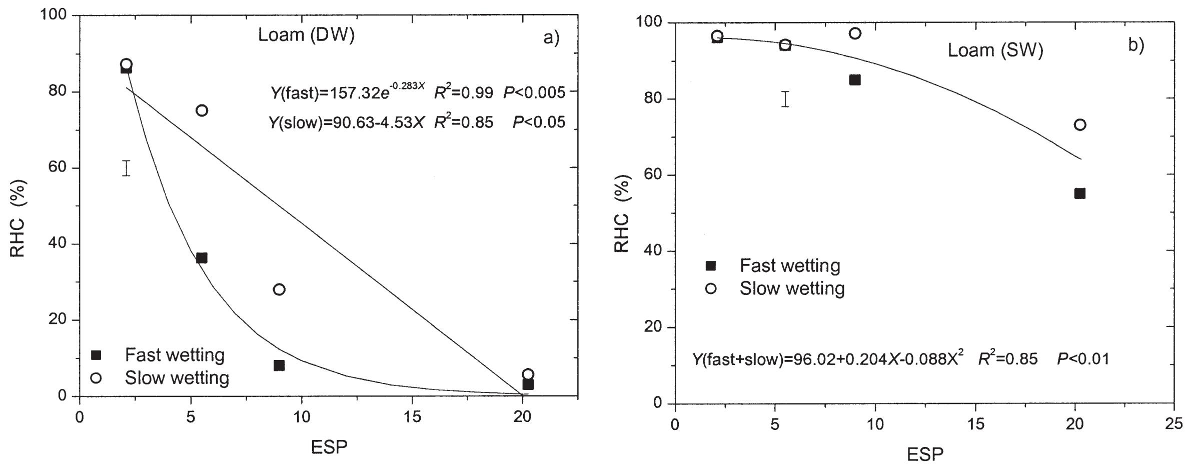

Fig. 6. Relative hydraulic conductivity at steady state (RHC) in the loam as a function of exchangeable sodium percentage (ESP), water quality, and rate of wetting: (a) distilled water (DW) treatment; (b) saline water (SW) treatment. Bars indicate a single confidence interval value at $P = 0.05$.

When saline water was used, RHC of the loam was not significantly affected by the rate of wetting in the range of ESP ≤ 5. A decreasing quadratic polynomial type curve described the relation between the RHC and ESP (Fig. 6b), indicating that only at ESP = 20, HCss was significantly lower than HCo for both fast and slow wetting. The presence of electrolytes in the leaching solution prevented clay dispersion; thus, only clay swelling could affect the HC. Apparently, only at high sodicity (ESP = 20) was the degree of swelling of soil samples, coupled with a slightly higher clay content (30% clay), severe enough to cause the HC to decrease to <75% of its initial value (Fig. 6b).

In general, the combined effects of water quality, rate of wetting, and sodicity on the RHC of the sandy clay were similar to those noted in the loam (Fig. 7 and 6, respectively). Because of significant differences in the mechanical composition of the two soils, the explanations for the results differ and justify a separate discussion. Clay content in the sandy clay was nearly 1.5 to 2 times higher than that in the loam (Table 1), which made the stability of the sandy clay aggregates significantly higher than that in the loam over the entire ESP range used in the current study (Levy et al., 2003). Consequently, the effects of wetting rate on aggregate slaking were more pronounced in the sandy clay (Shainberg et al., 2001). It is postulated that, in the sandy clay, the decrease in RHC with the increase in sodicity for leaching with distilled water (Fig. 7a) was due to clay swelling. When fast wetting was used, swelling resulted in lower RHC compared with slow wetting, mainly at the lower end of the ESP range studied and to an exponential type of decay in the RHC with the increase in sodicity (Fig. 7a), because aggregate slaking contributed to narrowing of the water conducting pores. Conversely, for slow wetting, similar to the loam, aggregates were maintained intact during the wetting procedure, causing clay swelling to have a more moderate effect on the decrease of RHC as a function of sodicity (Fig. 7a; Table 4). At the highest ESP studied (ESP = 20), swelling of the ≈40% clay in this soil was severe enough to overshadow the effects of wetting, and therefore similar RHC values were noted for fast and slow wetting (Fig. 7a).

In the case of leaching with saline water, the only mechanism that could have affected the RHC was clay swelling. Hence, similar to the loam, only when the ESP

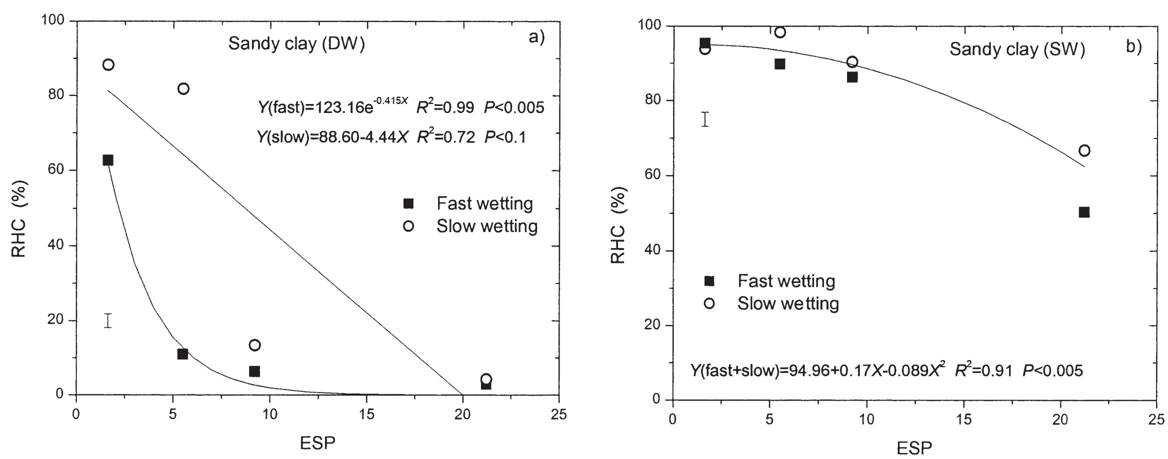

Fig. 7. Relative hydraulic conductivity at steady state (RHC) in the sandy clay as a function of exchangeable sodium percentage (ESP), water quality and rate of wetting: (a) distilled water (DW) treatment; (b) saline water (SW) treatment. Bars indicate a single confidence interval value at $P = 0.05$.

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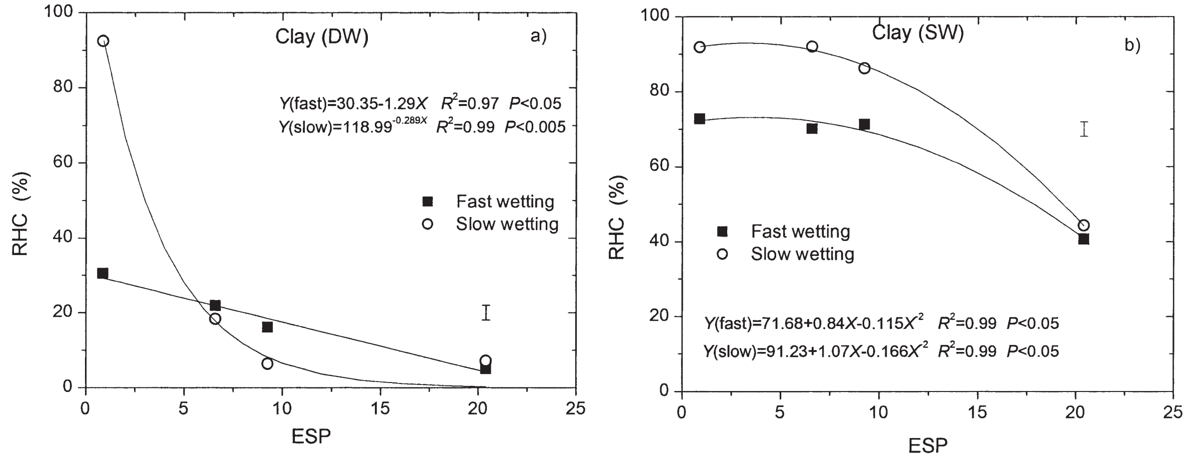

Fig. 8. Relative hydraulic conductivity at steady state (RHC) in the clay as a function of exchangeable sodium percentage (ESP), water quality and rate of wetting: (a) distilled water (DW) treatment; (b) saline water (SW) treatment. Bars indicate a single confidence interval value at *P* = 0.05.

reached 20, swelling of the clay was of a high enough magnitude that was sufficient to cause the HC to decrease to <75% of its initial value (Fig. 7b).

The dependence of the RHC in the clay on sodicity differed from that noted in the other three soils. Because of its high clay content (≈60%), the clay is characterized by high aggregate stability (Kemper and Koch, 1966; Levy et al., 2003). Conversely, the high clay content made this soil to be very sensitive to swelling, especially when distilled water was used. Already at ESP = 2, the RHC for fast wetting was <40%, and further decreased almost linearly with the increase in ESP (Fig. 8a). At slow wetting, the RHC for ESP = 2 was high (92%); however, for the other three ESP levels studied, the RHC was similar to that obtained for fast wetting (Fig. 8a), suggesting that for leaching with distilled water, swelling had a prominent role, independent of that of wetting rate, in determining the HCss. Thus, in contrast to the loam and sandy clay, the absolute value of the exponent of equation (exponential decay) for slow wetting was significantly higher than that for fast wetting rate (Table 4).

In contrast to the other three soils, RHC in the clay was affected by the rate of wetting during leaching with saline water (Fig. 8b; Table 4). The lower RHC values for fast wetting compared with slow wetting for ESP ≤ 10 suggested that albeit the use of saline water, some swelling occurred, that in the case of slaked aggregates (i.e., the fast wetting treatment) had even a more severe effect on reducing the HCss than when slaking of aggregates was prevented. On the other hand, once sodicity level was high (ESP = 20), clay swelling was apparently high enough (due to the high clay content in this soil) to solely control the degree of reduction in the HC, and thus similar RHC values were obtained for fast and slow wetting (Fig. 8b).

CONCLUSIONS

We studied the combined effects of water quality, ESP, and rate of wetting on the initial, steady state, and relative HC of four semiarid smectitic soil types varying in texture. The adverse impact of sodicity on the HC of soil samples subjected to fast wetting, combined with leaching with distilled water, strongly depended on soil texture. Because of poor aggregation, aggregate slaking played a negligible role in determining the HC in the loamy sand. Consequently, both the HCo and the RHC were predominantly affected by water salinity and soil ESP. In the loam, sandy clay, and clay soils, a significant triple interaction among water quality, wetting rate, and ESP in their effects on HCo and RHC existed, suggesting that the combined effects of these variables on the HC were complex. For distilled water treated samples, the impact of fast wetting and swelling on the HC was most notable at the intermediate sodicity levels

Table 4. Effect of wetting rate, sodicity, and water quality on parameters of the equation describing the relationship between RHC and ESP for both wetting rate and water quality.

	Distilled water			Saline water			
		$Y = ae^{-bX}$			$Y = aX^2 + bX + c$		
Soil	Wetting rate	a	$-b$	Wetting rate	$-a$	b	c
Loamy sand	fast	91.22c†	0.061d	fast	0.026c	0.501a	92.12a
	slow	115.98bc	0.043d	slow	0.022c	0.82a	92.10a
Loam	fast	157.31a	0.283b	fast	0.067bc	−0.81b	98.73a
	slow	121.78ab	0.129c	slow	0.109ab	1.22a	93.31a
Sandy clay	fast	123.17b	0.415a	fast	0.085b	−0.32b	95.59a
	slow	119.74b	0.137c	slow	0.093b	0.66a	94.31a
Clay	fast	33.59d	0.078cd	fast	0.115b	0.84a	71.68b
	slow	118.19bc	0.289b	slow	0.165a	1.07a	91.23a

† Values of equation parameters in the same column that are labeled with same letter are not significantly different at *P* = 0.05 level.

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(ESP = 5 and 10). However, at ESP = 20, the effect of clay swelling on reducing the RHC was overshadowing that of the rate of wetting, particularly on clayey soils. Use of saline water reduced the impact of fast wetting and swelling on both HCo and RHC. Concerning the RHC, some clay swelling took place in samples with ESP = 20 during the leaching of the columns albeit the presence of electrolytes, thus resulting in a lower RHC compared with samples with lower ESP levels. This phenomenon was most notable in the samples from the clay soil.

Saline and sodic conditions are frequently observed in semiarid regions. Deterioration in permeability to water of sodic soils can be alleviated even at high ESP by controlling the wetting procedure and maintaining the electrolyte concentration of the percolating water above a critical threshold level. It should therefore be realized that the dependence of soil HC on salinity, sodicity, and rate of wetting should not be considered independently but simultaneously, to better simulate possible conditions that may prevail in the field.

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